LASER REQUIREMENTS AND PERFORMANCE

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The Title I Design for the NIF meets all baseline performance requirements of our users from the ICF, weapons physics, and weapons effects communities. The Title I Design is a refinement of the NIF conceptual design and includes 16 amplifier slabs for each of the 192 beams and a total of 48 preamplifier modules (for all 192 beams) for the initial configuration. Laser performance for this configuration was validated with performance models and Beamlet data.

User Requirements

The Title I Design for the NIF takes into account the requirements and requests of our three main user communities. The top-level performance requirements for the NIF were driven by the indirect- (x-ray-) drive, ICF mission. Those requirements are as follows:

- 1.8 MJ of laser pulse energy on target.
- Flexible pulse shaping (dynamic range >50).
- Peak power of 500 TW.
- Pulse wavelength in the ultraviolet (0.35 μm).
- Beam power balance better than 8% over 2 ns.
- Pointing accuracy <50 μm.
- Compatibility with cryogenic and noncryogenic targets.
- Ability to do 50 shots per year, each with a yield of 20 MJ, for a total 1200 MJ annual yield.
- Maximum credible DT fusion yield of 45 MJ.
- Ability to perform classified and unclassified experiments.

In addition to these capabilities, weapons physics users want to have the highest possible peak power for short pulses (>750 TW at 3ω for 1 ns) in order to reach high temperatures and a range of pulse lengths from 0.1 to 20 ns for a wide variety of experiments. These users want bright sources for experiments requiring x-ray backlighting, with small spots at high temperatures (half the energy in a 100-μm spot, and about 95% of the energy at 200 μm). The beams for these backlighters must be pointed a few centimeters away from the center of the main target chamber.

Weapons effects users want the ability to locate arrays of laser targets several tens of cm from the target chamber center, as well as 1ω and 2ω capability. Their other requirements include access to the chamber for large, heavy test objects, a well-shielded diagnostics area for testing electronic systems, and no residual light on the test objects.

The NIF target chamber will also have ports that allow the beams to be placed in the proper location for direct-drive ICF experiments and for tetrahedral hohlraums as well as for the baseline cylindrical hohlraums. All these requirements mean that the NIF must accommodate experiments spanning a wide range of operating conditions (see Figure 1).

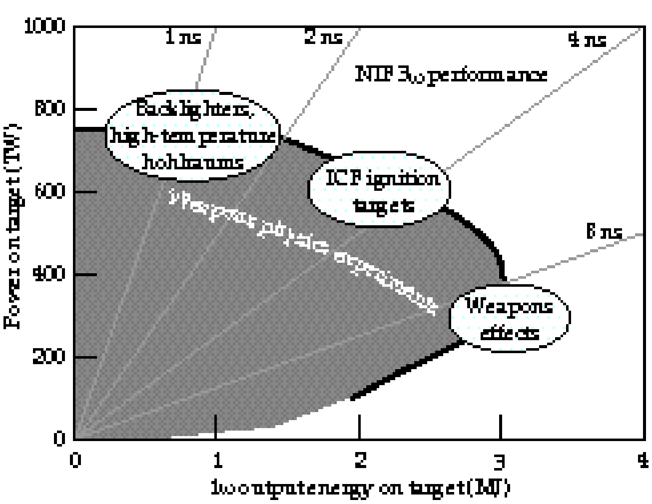

FIGURE 1. NIF users have identified important experiments spanning a wide range of operating conditions. (40-00-0997-1998pb01)

Laser Design Highlights

The NIF laser system, as it appears in the Title I Design, provides routine operation at 1.8 MJ / 500 TW in an ignition-target-shaped pulse and has a wide range of operation to meet other user requirements. The laser uses neodymium glass amplifier slabs, with 192 beams in a multipass architecture. The beams are grouped in 4 × 2 bundles and have an amplifier clear aperture of 40 × 40 cm^2. Frequency conversion is to the third harmonic, i.e., 3ω (350 nm). The laser has adaptive optics (deformable mirrors) to control the beam quality and uses kinoforms and smoothing by spectral dispersion (SSD) to control the beam quality on the target.

This design of the NIF laser system is essentially the same as what appears in the Advanced Conceptual Design (ACD) and is modified only slightly from the original conceptual design.However, due to the design-to-cost considerations, some features will not be implemented as part of the initial activation, most notably the 11-7 amplifier configuration and 192 preamplifier modules (PAMs). Instead, the initial NIF system will have an amplifier configuration of 11-5 and 48 PAMs. (This is similar to Beamlet, which is the scientific prototype for NIF.) This configuration can meet all NIF requirements, although with less performance margin than the 11-7 configuration, and it is less expensive to build. The laser and facility design are such that two additional amplifier slabs and 48 more PAMs can be added easily later. Other changes in the laser design include changing the baseline laser bundle size from 4 × 12 to 4 × 2 to simplify maintenance and raise the shot rate.

This design does preclude some options. For instance, there cannot be more than one color within each 2 × 2 beam quad, although different colors in different quads of beams or different cones are still possible. In addition, to bring the system back up to the original 192 preamplifier modules, while possible, would require major modifications to the laser support structure.

Laser Design and Performance

We use three methods to project the NIF laser's performance and safe operating limits. First, we calculate laser performance using simple scaling relations and propagation models. Second, we perform full propagation simulations using fast Fourier transform propagation codes, with simulated phase noise on each component based on measurements of Beamlet components. The codes also incorporate the calculated damage and filamentation risk at each component (Figures 2 and 3), and a full simulation of frequency conversion, including the beam quality and bandwidth. Finally, we compare these predictions to experimental results from Beamlet and Nova to be sure that the codes accurately predict what we expect to see on NIF.

Many of the propagation simulations were for a 2.2-MJ / 600-TW pulse, about 20% higher than the 1.8-MJ / 500-TW pulse required for routine ignition-target- shaped pulses. This 20% performance margin allows us to maintain the required output energy under less than ideal conditions. Conditions affecting output include looser performance specifications, out-of-specification components, beam balance issues, component degradation over time, and stressing operating conditions, such as broadband SSD for direct-drive targets.

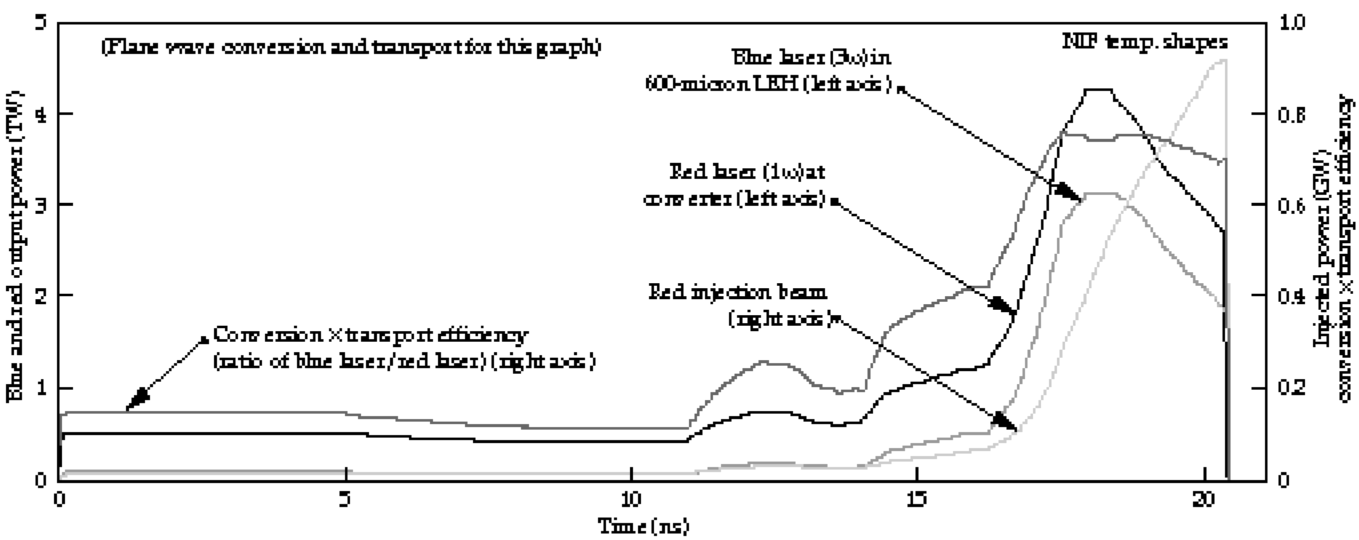

FIGURE 2. The nominal NIF 3ω ignition target pulse shape and the 1ω pulse shape required at the frequency converter and at the injection mirror (PABTS) to generate that pulse, as evaluated from a full NIF beamline simulation using LLNL propagation codes. Table 1 (on p. 102) summarizes other features of the simulation. (40-00-0997-1760pb01)

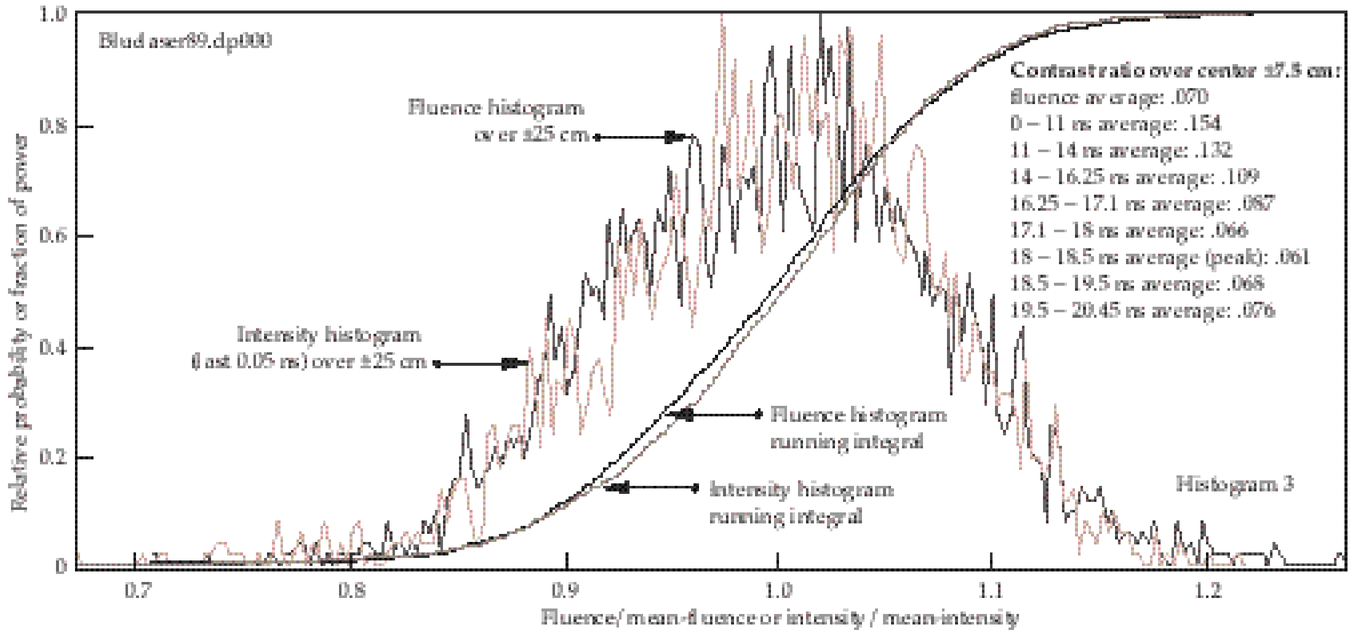

FIGURE 3. Simulated beam fluence and intensity distribution over aperture at frequency converter output (3ω) for an ICF pulse simulation. (40-00-0997-1761pb01)

Selecting the NIF Laser Design

The NIF laser design described in the ACD meets requirements, but—as mentioned above—it was necessary to determine whether a less expensive design could also meet the baseline performance requirements. In this section, we compare the NIF design from the ACD (11-7 slab configuration with 192 preamplifier modules) to less expensive options with fewer slabs and preamplifier modules that can be upgraded to the full ACD configuration.

The most important limit to the irradiance (power per unit area) and fluence (energy per unit area) of a glass laser system is damage to optical components in parts of the beam that have high irradiance or fluence. Because we wish to make the laser as inexpensively as possible, we need the smallest possible beam area—the laser cost for a multibeam system scales proportionally to the total beam area. Inevitably, then, damage to optical components is a major issue. The laser beam must have a highly uniform, flat fluence profile that fills the amplifier aperture as fully as possible. Also, we must minimize intensity noise on the beam, since these local regions of higher intensity may lead to local damage and may also grow due to nonlinear propagation effects in the amplifiers.

Tests on Beamlet, the NIF scientific prototype, and supporting modeling with detailed propagation codes show that nonlinear growth of intensity noise on the beam is small for operating conditions that keep the average nonlinear phase shift between any two spatial filter pinholes to less than 1.8 rad, as shown in Figure 4. For larger phase shifts, intensity noise grows very quickly. Therefore we use 1.8 rad of nonlinear phase shift between pinholes as the safe operating limit for NIF. For long pulses, there is an additional energy limit. The amplifiers store a limited energy per unit area, and there is a practical limit to the output energy when so much of that energy has been extracted that the input energy to the final stage must rise to a very high value.

These operating limits appear on the power vs energy diagram in Figure 5. The safe operating limits shown are limited by nonlinear noise growth at the top

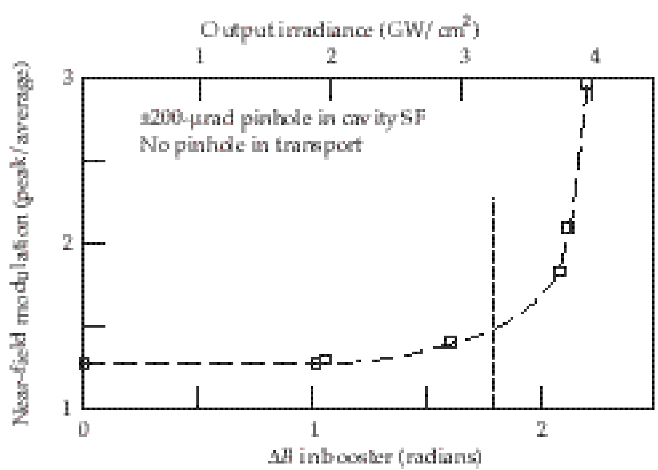

FIGURE 4. Beamlet data show that there is little nonlinear intensity noise growth for $\Delta B < 1.8$ rad. (40-00-0997-1999pb01)

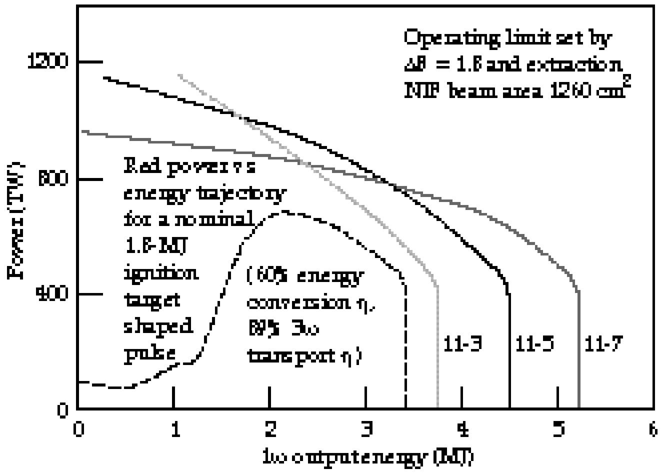

FIGURE 5. An 11-5 amplifier configuration meets the NIF requirements (1.8-MJ shaped pulse), but with less margin than 11-7. (40-00-0997-2000pb01)

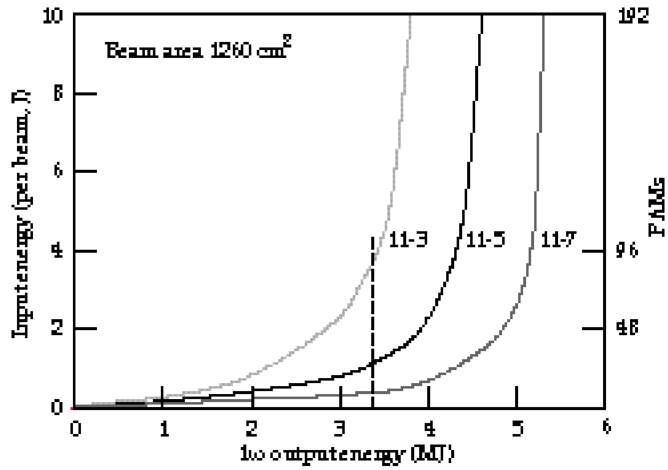

FIGURE 6. The 11-7 and 11-5 amplifier configurations have adequate performance with 48 preamplifier modules. (40-00-0997-2001pb01)

of the figure and by energy extraction at the maximum practical energy at the vertical line to the right. A "square" flat-top pulse of constant intensity has a trajectory on this figure that follows a line of constant power from the zero-energy axis on the left to the end of the pulse at time τ, where it drops vertically to zero. The maximum nonlinear phase shift occurs exactly at the end of the pulse, so the closest approach to the laser safe operating limit occurs exactly at the end of the pulse. Square pulses of different power and energy but constant pulse length τ lie on a straight line through the origin of the figure.

The shaped pulses required for fusion have a somewhat more complex behavior, as shown by the power-energy trajectory of a nominal ignition target pulse in Figure 5. The intensity of these pulses can be lower at the end than earlier in the pulse, so the closest approach to the safe-operating-limit line can occur partway through the pulse.

Figure 5 shows that 11-7 and 11-5 laser amplifier configurations can both generate sufficient laser output to meet the requirements of a nominal 1.8-MJ 3ω target-drive pulse that requires about 3.4 MJ of 1ω drive in the shape shown. An 11-3 slab configuration can meet the requirement as well, but the margin is small.

The input drive required from the preamplifier is also important for comparing these systems. The proposed NIF preamplifier module can generate about 10 J, so if there is one module per beam (192 modules), it can safely drive any of these amplifier configurations to the required 3.4-MJ output for the nominal ignition target pulse, as shown in Figure 6. If we have one preamplifier module for four beams (48 modules), then the module can supply only about 2 J per beam, after inevitable losses. The 11-7 and 11-5 configurations still have adequate input drive under these conditions, but the 11-3 does not.

We must also consider the possible variations in component quality and performance from those assumed in generating these figures, although we believe the nominal assumptions used there are the most probable result for NIF. We might test, for example, the sensitivity of the performance curves to a range of possible performance variations for the NIF amplifiers. Table 1 shows a range of possibilities for these parameters, with those chosen as most probable and assumed for the baseline analysis appearing in white boxes. Figure 7 shows a gray-shaded

TABLE 1. The design models are used to study sensitivity to variations in component performance. Those values assumed for the baseline analysis appear in white boxes.

Sensitivity to amplifier performance			
	Low value		High value
Slab transmission	0.985	0.9945	0.9975
Gain coefficient multiplier	0.95	1.0	1.05
Glass type	all LG770	50:50	all LHG-8
Gain rolloff (fraction of Beamlet value)	1.0	0.75	0.5

Values assumed in NIF baseline model

range over which the safe operating limit of an 11-5 NIF amplifier configuration would vary between the best and worst cases generated by combinations of the ranges in Table 1. The 11-5 configuration meets the 1ω drive requirements for the 1.8-MJ 3ω ignition target pulse even in the worst-case combination of these variations. The gray-shaded zone for the 11-3 configuration is of comparable size to the one shown in Figure 7, so that configuration clearly fails to meet the requirements over a wide range of possible component variations. The 11-7 (Figure 8) has more performance margin than the 11-5 and could tolerate a more severe combination of performance degradations than assumed in Table 1, which the 11-5 could not.

These amplifier variations also affect the input drive required from the preamplifier module. Figure 9 shows a gray-shaded range of input energy required for the 11-5 configuration over the range of variation in Table 1. The 48-PAM case has adequate input drive to reach the nominal ignition requirements over a fairly wide range of variation, but some unfavorable combinations could require 96 PAMs.

After careful study with analyses such as these, supported by detailed simulations, we decided to reduce the NIF laser hardware cost by changing to an 11-5 amplifier configuration and reducing the PAM count to 48. Since Figure 9 shows there is some risk with 48 PAMs, we chose at Title I to make the system easily upgradable to 96 PAMs. We also plan to revisit the PAM design early in Title II (final design) to see whether the design can be increased in size at modest cost to cover up to the drive energy of roughly 4 J per beam that would be required in a worst case.

With these choices, the NIF laser design is now essentially the same as the design we first chose for the Beamlet scientific prototype for NIF; tests of the Beamlet laser[1] show in detail that the 11-5 laser architecture and performance work. There are minor differences having to do with beam injection and component size and spacing, but the basic performance should be very similar. This assumes, of course, that

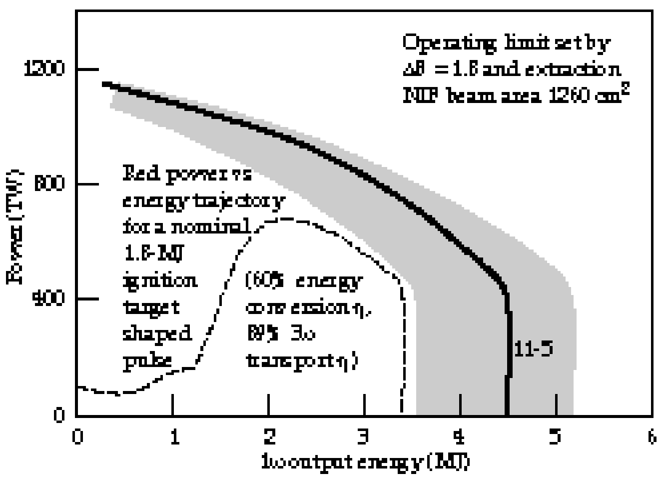

FIGURE 7. An 11-5 NIF has a small performance margin above the requirement over this range of amplifier variation. (40-00-0997-2002pb01)

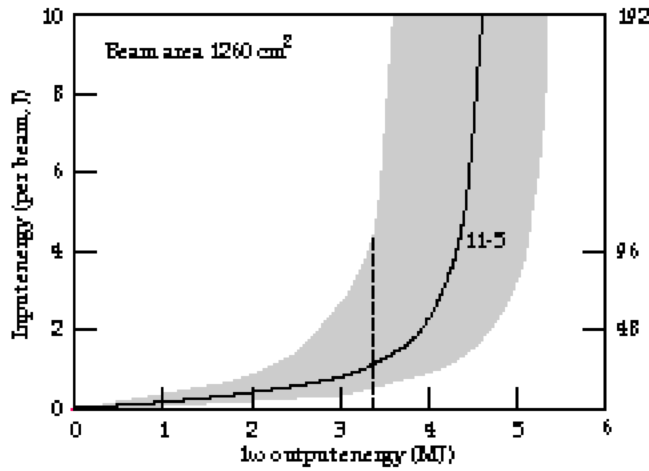

FIGURE 9. The input energy requirements for an 11-5 NIF are acceptable for 48 PAMs over this range of amplifier variation. (40-00-0997-2004pb01)

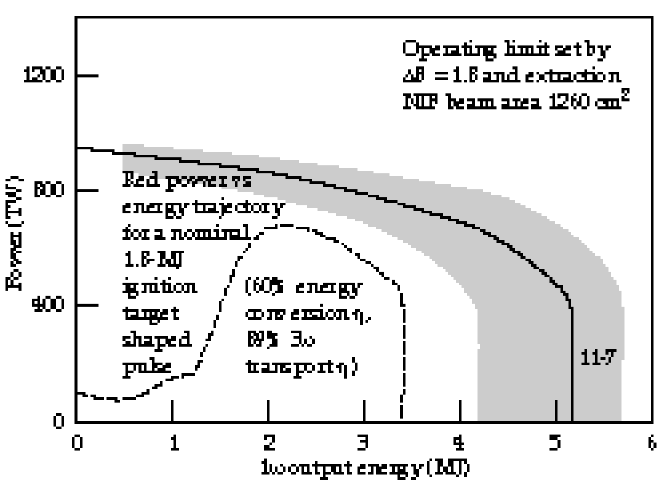

FIGURE 8. An 11-7 NIF has a significantly larger margin than an 11-5 over this range of amplifier variation. (40-00-0997-2003pb01)

we can get components such as laser slabs in quantities of several thousand at the same quality we see in quantities of twenty, which is the point of studying the effect of variations such as those in Table 1. Figure 10 shows that we have operated Beamlet for about 50 shots at or slightly beyond the safe operating limits projected for NIF, with acceptable intensity modulation and damage. Note that the figure scales Beamlet shots to the NIF beam area at constant fluence, which is the important parameter for comparisons of performance. The Beamlet beam area is smaller than NIF (34 to 35 cm^2 vs 37.2 to 37.8 cm^2 at zero intensity), so 192 Beamlet beams would give somewhat less energy than shown on Figure 10.

So far, we have considered only the 1ω performance of the laser. Laser damage thresholds are a factor of two or more lower at 3ω than at 1ω, and the effect of nonlinear propagation is a factor of four worse for a given length of material. Therefore we designed the laser so that the frequency conversion happens as close to the target as possible and so that the optical components that see 3ω light are as thin as possible. Many users want the highest possible peak power from NIF at short pulses. As a result, we changed the final optics package from the original conceptual design to use a color separation grating rather than a wedged lens, allowing the lens to be about half its original thickness and giving higher peak power with short pulses. The lens was originally the vacuum barrier to the target chamber, as on Nova, but this requires a thicker lens for safety and would severely restrict the short-pulse performance of NIF. Therefore we have changed the design so that the vacuum barrier is a window in the 1ω beam where damage and nonlinear effects are less important.

Beamlet has a frequency conversion package similar to that designed for NIF, and we have studied the performance of this converter and shown that its performance agrees well with simulation codes. Figure 11 shows the projected performance of NIF at 3ω, delivered to target chamber center, with our nominal design assumptions. For short pulses below about 2 ns, the 3ω performance is limited by beam breakup due to nonlinear index effects in the 3ω optics. Pulses from about 2 to 8 ns are limited by nonlinear effects in the 1ω part of the laser and possibly by damage thresholds of the 3ω optics, depending on how successful we are at acquiring consistently high-quality material and finishing. Long pulses are limited by the energy extraction limit of the laser, together with increasingly inefficient

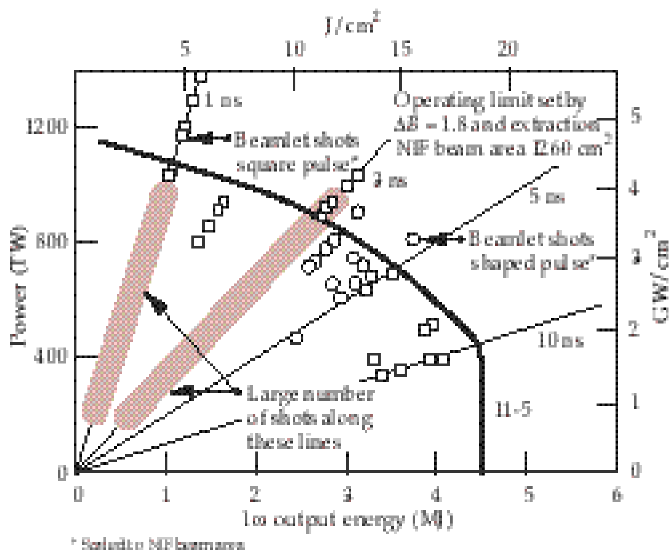

FIGURE 10. Beamlet has fired about 50 shots near or slightly over the 1ω safe operating limits projected for an 11-5 NIF. (40-00-0997-2005pb01)

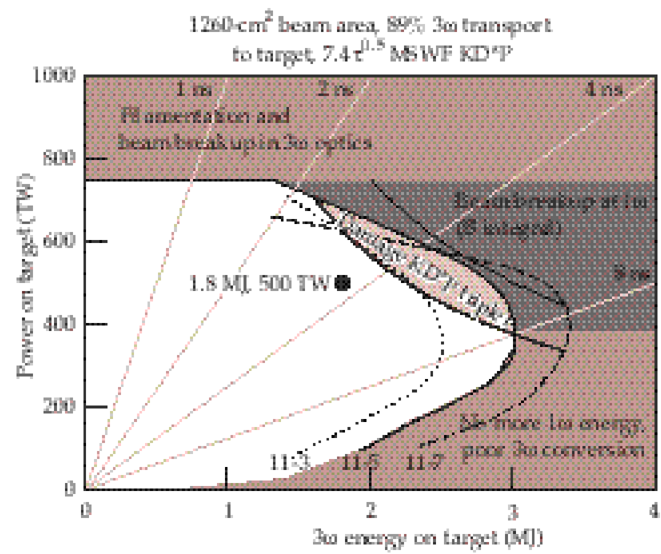

FIGURE 11. NIF 3ω power and energy delivered to target. (40-00-0997-2006pb01)

frequency conversion as the 1ω laser irradiance decreases.

Beamlet will test a "brassboard" version of the NIF final optics assembly in late 1997. We have, however, studied 3ω optical performance with a configuration using a much thicker wedged lens, like the one appearing in the original conceptual design. Shots at 0.2 to 1 ns and at an irradiance corresponding to 750 TW on target for NIF caused a few (~10) damage spots in the focus lens from self-focusing of local hot spots on the beam. This is an acceptable level of damage, and in addition, the thinner lens in the current NIF design will further reduce filamentation. Several shots at irradiance and fluence corresponding to 600 TW, 1.9 MJ on target caused no damage to the frequency-tripler crystal, which is the component we expect to have the lowest 3ω bulk damage threshold. There were a few damage spots to the surface of the 3ω focus lens, showing the importance of quality control over surface finishing of high-fluence 3ω components. Although components of adequate damage threshold have been fabricated by vendors, this area remains a principal concern of the Project.

Conclusion

The Title I Design for NIF will meet the top-level performance requirements with an 11-5 amplifier configuration and 48 preamplifier modules, according to performance models and data from Beamlet. Tests of the Beamlet laser[1] show that the 11-5 laser arcitecture and performance will meet and support the NIF requirements. The performance margin is less than that for the 11-7 configuration: component performance is more critical and the energy and power is less for stressing operating conditions. However, if a larger performance margin is desired, the design is such that 2 amplifier slabs and 48 additional PAMs can easily be added later.

Reference

1. Van Wonterghem et al., *Applied Optics* **36** (21), 4932 (1997).

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